29th International Cosmic Ray Conference Pune (2005) 8, 121-124

UHECR observation from space and the ESA Cosmic Vision Programme

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The astrophysical and physical processes at the very end of the known energy spectrum, in the region of the so-called Ultra High Energies (UHE), have been the subject of an intense debate in the last years. UHE particles are nucleons, nuclei, photons, and neutrinos or even new particles predicted by theory, but not discovered yet, with energies from a few 10^{18} eV, where fluxes of cosmic neutrinos are expected from "standard" physics and astrophysics, to beyond the decade of 10^{20} eV, where radiation is thought to be produced under the most extreme physical conditions in the Universe. The understanding of the nature, origin, propagation to Earth of such UHE particles would provide entire new information on the sources and the astrophysical mechanisms that could produce them. Moreover, observations at UHE, would, possibly, allow us to test high energy physics beyond the limit of existing and next generation accelerators as well as Lorentz invariance at extreme energies. The ground-based Pierre Auger Observatory, whose southern site is currently being completed in Argentina, will surely provide, in the near future, more solid observational bases for the understanding of what is today the UHE puzzle. However, in any post-Auger scenario, only space-based observatories can reach the collecting power necessary to fully explore the UHE Universe, establishing then "Particle Astronomy" as a new observational window. Building on the studies conducted for the ESA-led Mission EUSO, we summarize here: 1. the science goals of an ESA "Cosmic Vision 2015-2025" mission for UHE search; 2. Its scientific requirements; 3. The necessary R&D preliminary to any further development of such a challenging innovative mission.

1. Introduction

UHECR- Uniformly distributed in the sky, with no evidence of an enhancement in the galactic plane, UHECR are thought to be coming from extragalactic distances. However the Universe is thought to be opaque at $E > 5\times10^{19}$ eV, the energy, for protons, of the Greisen Zatsepin and Kuzmin (GZK) effect [1,2]. Interacting with the 2.7 °K photons of the CMB via photo-pion production, protons or charged ions lose energy while propagating to the Earth. Their propagation distance is limited to less than 100 Mpc and a "cut-off", or rather a "flux suppression", is expected in the observed UHECR spectrum [3,4], coupled to a copious ultra high energy flux of "cosmogenic" neutrinos (GZKν) whose intensity should peak at an energy of 10^{18} eV.

The existence of such UHE events is well established: six different experiments, spread along almost half a century, have reported evidence for ~20 events with $E>10^{20}$ eV, and with a maximum of $E\sim3\times10^{20}$ eV [5]. However, the flux and the shape of their spectrum, measured by the AGASA observatory [6], which reports no evidence for a GZK cut-off, does not agree with the one observed by the HiRes experiment [7], consistent with the GZK hypothesis. Moreover, a small scale clustering of events (1 triplet and 5 doublets), indication of possible compact sources of UHECR, has been observed by AGASA [8] and not confimed by HiRes.

Ultra High Energy Neutrino Astronomy, which will unveil regions of the Universe otherwise shielded, is another of the exciting possibilities that is expected to be opened by the next generation of UHE observatories. Although no UHE neutrinos (UHEν) have yet been observed, these are expected in all the models conceived so far to explain the UHECR. In particular at low energies, in the $E \sim 10^{18}$ eV range, the GZKν flux appears to be significant and a precise measurement of the UHECR flux is strongly coupled to a quantitative estimate of this flux. In the same energy region measurable fluxes of neutrinos from cosmic sources are expected. Bottai & Spillantini, [9, and references therein] have estimated observable neutrino fluxes based on both "speculative" (Top-Down, ZBurst, Super Massive Relic) and "standard astrophysics" models (AGN and GZK). These are shown in Figure 1 (courtesy of S. Bottai). The dots in the figure set the sensitivity requirement for "granted" observable fluxes of neutrinos.

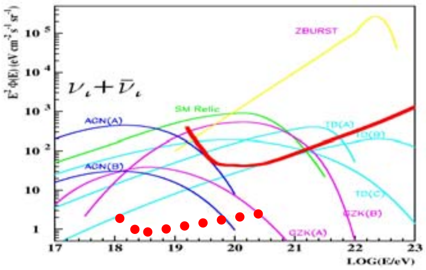


Figure 1. Neutrino fluxes per flavour (full mixing neutrino oscillation scenario) predicted by several bottom-up and top-down models. The red thick line represents the neutrino flux per flavour which produces one events/year per energy decade in EUSO. Details on the models and EUSO simulation can be found in ref. [9,10]. The dots set the sensitivity requirement for "granted observable" flux of neutrinos and therefore for any novel mission for UHE neutrino research.

A Lab for Physics at UHE ?- Provided the adequate statistics, Observations of UHECR and UHEν will, possibly, allow us ***to test high energy physics beyond the limits of existing and next generation accelerators.*** The potential of physics discoveries of such a theme appears, indeed, to be excitingly large. In the near future accelerator experiments might reveal new physics predicted at TeV scale. However, to go beyond this we have to turn to cosmic accelerators: particles whose energies reach 10^{20} eV are indeed observed. This dwarfs the energies achieved in laboratory experiments by about three orders of magnitude in the centre of mass. New particles might be discovered and UHECR could help to investigate the properties of those particles at much higher centre of mass energies. As an example, a comparison of rates and air shower structure of Earth skimming events and deeply penetrating/horizontal events could allow to test cross sections of weakly interacting particles, such as neutrinos or, potentially, yet undiscovered particles such as neutralinos, at energies unattainable by any terrestrial accelerator.

2. The Science Case for a Cosmic Vision space-based mission.

In the near future, the largest ground-based experimental facility for UHECR research is *The Pierre Auger Observatory* (PAO) [11] whose southern site is currently being completed in Malargue, Argentina. The PAO detection system combines an array of 1600 particle detectors, which measure the lateral distribution of particle density, and 4 fluorescence detector stations, to measure the longitudinal profile of the EAS. Auger South, that has an effective area of $A^{eff}_{Auger} \sim 7\times10^3\ km^2\ sr$, equal to its instantaneous aperture, is expected to clarify the observational scenario on UHECR observing the existence/non-existence of any GZK signature in the UHECR spectrum and possibly discovering sources of UHE particles. Auger studies might be extended to the northern hemisphere with a second site, as of today, in its final approval phase.
However, as far as the post-Auger future is concerned, we quote a statement by the PAO collaboration board: *"Although it is impossible to predict what Auger will find in the next few years, it seems certain that it will be necessary to monitor massive volumes of atmosphere to study charged cosmic rays and neutrinos at UHE. Observations from a space platform are likely to be essential, particularly for the study of very high energy neutrinos"*. J. Linsley firstly suggested that the Earth's atmosphere viewed from space at night constitutes a huge calorimeter for remotely observing UHECR [12]. Indeed only space-based observatories, with a practical limit for the instantaneous aperture of $A_{inst} \sim 10^7\ km^2\ sr$ might reach the collecting power

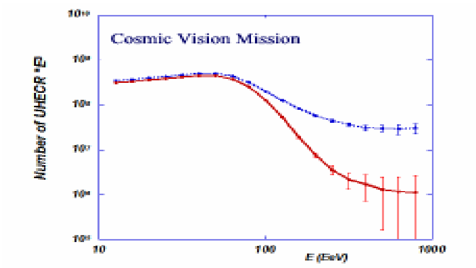
needed to fully explore the UHE Universe, therefore establishing "Particle Astronomy". For each shower, the (330-400 nm) fluorescence track as a function of the slant depth X, in the atmosphere, can be measured from space together with the diffusely reflected Čerenkov light, signature of the impact point of the shower front on the land, sea or cloud surface. The pathfinder in the field is the *"Extreme Universe Space Observatory– EUSO"* an European Space Agency (ESA) international mission designed for the Columbus module on the International Space Station (ISS). EUSO, which has an $A^{eff}_{EUSO} \sim (6\text{-}9)\times10^4\ km^2\ sr$, and an instantaneous aperture of $A^{eff}_{inst} \sim 6\times10^5\ km^2\ sr$, has successfully concluded the ESA Phase A study. Decision to proceed into phase B has not been taken yet due to financial and programmatic uncertainties related mainly to the ISS [13]. The upcoming generation of prototypal experiments, based on the fluorescence light detection from space, includes also the TUS and the KLYPVE missions [14] .
An extremely exciting opportunity to shape the next-generation mission for UHE research has been recently opened with the ESA's new long term plan for space science "Cosmic Vision 2015-2025". The plan will contain the scientific themes in space science to be tackled by ESA in the next decade and beyond. It is expected to be finalized by the end of July 2006. The major scientific themes have been already selected and among these "The search for the fundamentals laws of the Universe" which includes the "Exploration of the limits of contemporary physics" through, among other techniques, cosmic messengers at UHE. As a matter of fact, a mission for CR and ν search at UHE has been included in the plan, together and in competition with other "strategic" missions. Following the finalization of the Cosmic Vision Report a Call for Mission has been announced by ESA for early/mid 2006.

Having in mind the ESA Cosmic Vision program and timeline and building on the results expected from the currently planned observatories the science goals for the next-generation mission for UHECR research should aim at: 1. **A high statistics precision measurement of the UHECR spectrum** around and beyond the GZK "cut-off". Whereas sources at cosmological distances contribute to the cosmic ray flux below the GZK feature, the flux above this GZK feature measures the contribution of sources closer than a few tens Mpc. An exact measurement of the spectrum will thus probe the temporal evolution of cosmic ray activity in the Universe; 2. Identifying **individual cosmic sources** of UHECR and measure the **correspondent flux and energy spectrum**. This will shed light into the unresolved problem of the astronomical objects and physical mechanisms capable to accelerate particles to these extreme energies; 3. Using UHECR particles as probes for obtaining information on both ***the galactic and intergalactic magnetic fields*** about which little is known. Particularly when sources are identified, the intervening magnetic fields can be considered as spectrometers both to complement the measurements made and to deduce the magnetic fields themselves.

It's in the field of neutrino studies that a future UHE mission is expected to provide a real scientific breakthrough. In fact only a few UHE neutrinos will be detected by the current planned observatories and only if the most promising flux scenarios applies. Any next-generation mission should therefore aim at: 1. Detecting **cosmic sources of neutrinos** at UHE; 2. discovering the existence and **measure the flux of GZK neutrinos**; 3. measure the flux of neutrinos at UHE, above the GZK limit. Of course, if UHECR do not originate from astrophysical sources, entire new scenarios on physics beyond the standard model (discovery of new particles like *Axions, R-Hadrons)* or even on "new" physics (*Topological defects* and/or *Supermassive Relic particles)* could be opened.

3. Preliminary requirements, simulations and expected R&D.

As required by the above defined scientific goals, and based on the studies already conducted for the EUSO Mission the following scientific requirements can be preliminarily envisaged for this "Cosmic Vision" Mission: Effective Aperture→ $\sim 6\times10^5\ km^2\ sr$; Low energy threshold → $\sim 4\times10^{18}\ eV$ (mainly driven by neutrino search); Average angular resolution $\Delta\xi < 1°$; Energy resolution → $\Delta E/E \leq 0.1$; EAS maximum determination $\Delta X_{MAX} \leq 20 g\ cm^{-2}$; Orbit height → variable, *400-1000 km;* Operational life → Five full years on-orbit operational life. Preliminary simulations, based on these figures, are shown in Figure 2.



Red line: no sources within 5 Mpc
Blue line: 5 sources within 5 Mpc

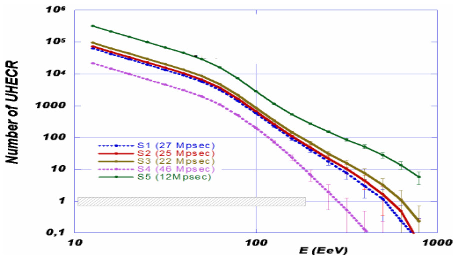


Figure 2 Left panel)- Assuming a source density of 10^{-5}/Mpc (~5 sources within 50 Mpc) [15], and a maximum input energy of E~10^{22} eV, the average UHECR spectrum measured by a "Cosmic Vision" type mission can be simulated. Statistics should allow precise measurement of the feature of the average spectrum, even resolved for selected region of the sky; **Right panel)-** Assuming, again, a source density of 10^{-5}/Mpc [15], we show that, when the requirements are met, individual spectra of UHECR sources can be resolved, for different distances of the sources. Simulation are also based to a code for propagation kindly provide to one the authors (EP) by Etienne Parizot (Orsay). Propagation takes into account photopion-production.

To meet the challenging scientific goals of such a mission within the Cosmic Vision timeline a vigorous R&D effort appears indeed necessary. Key items to be studied include: 1. Large area (*pupil ∅ → 5-7 m*) , large Field of View *(~60° full angle),* high throughput, light weight optical systems sensitive to UV; 2. deployability/assembling in space; 3. Large area, highly segmented *(10^6 channels)* detectors; 4. high quantum efficiency sensor *(QE > 50%);* 5. fast and smart on-board trigger electronics and data handling; 6. Innovative "free flyer" mission profiles for variable altitude orbits (from "low"-300 km to "high"-1000 km), flight configurations of two or more large field of view telescopes, operating in a stereo configuration. The possibility of having on-board high frequency radio systems capable to detect coherent radio pulses developed from UHE particles should be explored too [16]. Finally, In parallel with the R&D efforts, an experimental program for auxiliary measurements (300-400 nm UV background, fluorescence yield in space-like conditions, albedo of diffusively reflected Cherenkov light) should be also developed.

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